

THE ORIGIN OF VARIABILITY OF THE INTERMEDIATE-MASS BLACK-HOLE ULX SYSTEM HLX-1 IN ESO 243-49

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Abstract

The ultra-luminous ($L_X \lesssim 10^{42}$ erg/s) intermediate-mass black-hole system HLX-1 in the ESO 243-49 galaxy exhibits variability with a possible recurrence time of a few hundred days. Finding the origin of this variability would constrain the still largely unknown properties of this extraordinary object. Since it exhibits a hardness-intensity behavior characteristic of black-hole X-ray transients, we have analyzed the variability of HLX-1 in the framework of the disk instability model that explains outbursts of such systems. We find that the long-term variability of HLX-1 is unlikely to be explained by a model in which outbursts are triggered by thermal-viscous instabilities in an accretion disc. Possible alternatives include the instability in a radiation-pressure dominated disk but we argue that a more likely explanation is a modulated mass-transfer due to tidal stripping of a star in an eccentric orbit around the intermediate-mass black hole. We consider an evolutionary scenario leading to the creation of such a system and estimate the probability of its observation. We conclude, using a simplified dynamical model of the post-collapse cluster, that no more than 1/100 to 1/10 of $M_\bullet \lesssim 10^4 M_\odot$ IMBHs – formed by run-away stellar mergers in the dense collapsed cores of young clusters – could have a few $\times 1 M_\odot$ Main-Sequence star evolve to an AGB on an orbit eccentric enough for mass transfer at periape, while avoiding collisional destruction or being scattered into the IMBH by 2-body encounters. The finite but low probability of this configuration is consistent with the uniqueness of HLX-1. We note, however, that the actual response of a standard accretion disk to bursts of mass transfer may be too slow to explain the observations unless the orbit is close to parabolic (and hence even rarer) and/or additional heating, presumably linked to the highly time-dependent gravitational potential, are invoked.

Subject headings: X-rays: individual(ESO 243-49 HLX-1) – accretion, accretion discs – instabilities – stars: binaries: close – galaxies: star clusters – stellar dynamics

1. INTRODUCTION

HLX-1 is the brightest ultra-luminous X-ray (ULX; see Roberts 2007, for a review) source known, located in the outskirts of the edge-on S0a spiral galaxy ESO 243-49 with a maximum luminosity of $\sim 10^{42}$ erg s⁻¹ (Farrell et al. 2009; Godet et al. 2009). The recent dis-

covery (Wiersema et al. 2010) in the optical HLX-1 spectrum of an emission line consistent with H_α at the redshift of ESO 243-49 ($z = 0.0223$) irrevocably confirms its association with this galaxy at a distance of 95 Mpc. With observed X-ray luminosities reaching above 10^{42} erg s⁻¹ HLX-1 is super-Eddington if the black-hole's mass is less than $\sim 10^4 M_\odot$. Beaming effects (e.g. King 2008; Körding et al. 2002) have been proposed as viable mechanisms for producing the apparent super-Eddington luminosities seen from other ULXs. However, beaming is unlikely to explain HLX-1's extreme luminosity due to the observed large-scale variability (which appears similar to that seen from Galactic stellar mass black hole binaries that are not viewed down the jet-axis) and the luminosity of the H_α line (which is an order of magnitude above that expected from reprocessing in the local absorbing material; Wiersema et al. 2010). Based on AGN-type scaling the H_α luminosity might suggest a mass $\lesssim 1500 M_\odot$ (Wiersema et al. 2010), but since it is not clear how the line is related to the accreting system this estimate is highly uncertain. By taking the conservative assumption that HLX-1 exceeds the Eddington limit by no more than a factor of 10 (Begelman 2002), Farrell et al. (2009) placed a lower limit on the black hole mass of $500 M_\odot$. However, Godet et al. (2010) obtained from a disc-blackbody fit a peak luminosity of 1.3×10^{42} erg s⁻¹ (August 29, 2010) and a temperature 2.7×10^6 K. Comparing this value to that obtained from the (non-

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relativistic) formula for the effective temperature at the inner edge of an accretion disk around a black hole:

$$T_{\text{in}} \approx 6 \times 10^6 \left(\frac{L_{42}}{\eta_{0.1} M_4^2} \right)^{1/4} x^{-3/4} \text{ K}, \quad (1)$$

where L_{42} is the luminosity in units of $10^{42} \text{ erg s}^{-1}$, $\eta = 0.1\eta_{0.1}$ is the accretion efficiency ($\lesssim 0.4$), M_4 the black hole mass in units of $10\,000 M_\odot$ and $x = c^2 R/2GM$ is the radius measured in units of the Schwarzschild radius, one concludes that $M \gtrsim 10^4 M_\odot$.

This conclusion is supported by more refined methods such as fitting the *XMM-Newton* European Photon Imaging Camera (EPIC) spectra with various models (KerrBB, KerrD, slim-disc, BHSPEC) which favor a mass $M \sim 10^4 M_\odot$ (Godet et al. 2011; Davis, et al. 2011). The same is true of the normalization of the diskbb model. One should add that the temperature and luminosity observed during the previous luminosity peak (on the 2009-08-16; Godet et al. 2009) were very close to those determined recently.

After almost two years of monitoring with *Swift*, one sees that the X-ray light-curve of HLX-1 shows variability with a characteristic time of $\sim 10^7 \text{ s}$ (Fig. 1; Godet et al. (2010)). The available data seem to indicate a FRED (Fast Rise Exponential Decay) – type shape. The recurrence time seems to be $\sim 380 \text{ days}^{11}$ (consistent also with XMM1 and two Rosat observations, see Webb et al. 2011) and the decay-time from (the first) maximum is $\sim 90 \text{ days}$. The rise is very steep and occurs over a timescale of about one week. The amplitude of the X-ray variations is a factor of $\sim 20 - 50$. The decay-from-maximum light-curve shows small “re-flares” not dissimilar to those sometimes observed in low-mass X-ray transient sources (e.g. Chen et al. 1997). The end of the second outburst’s light-curve is typical of X-ray transients suggesting the propagation of a cooling front. In addition, the hardness of the X-ray spectrum of HLX-1 follows the trend observed in X-transients: it increases with declining luminosity. A recent deep observation with *XMM-Newton* on 2010 May 14 (MJD 55330) confirms that the spectrum does harden at lower luminosities ($\sim 3 \times 10^{40} \text{ erg s}^{-1}$; Servillat et al. in preparation). The analysis of these data suggests that there may be some unresolved contribution from the nucleus of ESO 243-49 in the X-ray emission. However, spectral modeling (using a thermal plasma model to represent emission from the galaxy) indicates that this is likely to contribute no more than $\sim 20\%$ of the total observed flux, and thus that the low state luminosity is dominated by emission from HLX-1.

These properties of the HLX-1 variability suggest that it could result from the same thermal-viscous instability that drives the outbursts of X-ray transient systems and dwarf-nova stars, and that the HLX-1 behaviour might be described by a variant of the corresponding disk instability model (DIM; see Lasota 2001, for a review).

2. ACCRETION DISK INSTABILITIES

2.1. Accretion disk size according to the DIM

The luminosity of HLX-1 ($\sim 10^{42} \text{ erg s}^{-1}$) and the variability timescale ($\sim 10^7 \text{ s}$) imply a huge accretion

rate onto the compact object, of the order of $10^{-4} M_\odot \text{ yr}^{-1}$. Sustaining such a high mass transfer rate excludes wind accretion. We will therefore assume that the putative stellar companion of HLX-1 fills its Roche-lobe, if only during part of its orbit, losing matter that forms an accretion disk around the black hole. This assumption is also supported by the observed intensity related spectral changes. The black hole mass is assumed to be around $10^4 M_\odot$ so the mass ratio $q = M_\bullet/M_*$, where M_\bullet and M_* are respectively the black-hole and stellar-companion masses, will typically be $q \approx 10^{-4} - 10^{-3} \ll 1$ and the Roche-lobe radius can be written

$$R_L = a(q/3)^{1/3}, \quad (2)$$

where a is the orbital separation (Paczynski 1977, for the moment we assume a circular orbit). When q is so small, matter circularizes very close to the donor star and the 2:1 Lindblad resonance appears at a radius $\approx 0.63a$ within the primary’s Roche lobe (Lin & Papaloizou 1979), affecting the accretion disk formation and structure (see Yungelson et al. 2006, for a discussion). In the following we will assume the disk forms and has a size $R_D \approx a$.

Here, we assume the variability in HLX-1 is related to the disk instability model. This requires that the disk is big enough to allow its temperature to fall below the temperature where hydrogen recombines (Lasota 2001). According to the DIM the accretion rate at outburst maximum is nearly constant through the disk and roughly equal to the (upper) critical accretion rate (Lasota et al. 2008):

$$\dot{M}_{\text{crit}}^+ \approx 3 \times 10^{-6} \alpha^{-0.01} R_{13}^{2.64} M_4^{-0.89} M_\odot \text{ yr}^{-1}, \quad (3)$$

where R_{13} is the disk radius in units of 10^{13} cm and $M_\bullet = M_4 \times 10^4 M_\odot$ is the mass of the black hole. This limit is essentially independent of the Shakura-Sunyaev disk-viscosity parameter α . Therefore the maximum (bolometric) luminosity is equal to

$$L_{\text{max}} \approx 1.6 \times 10^{40} \eta_{0.1} R_{13}^{2.64} M_4^{-0.89} \text{ erg s}^{-1}. \quad (4)$$

Hence for L_{max} the disk radius will be equal to

$$R_D^{\text{max}} \approx 5.2 \times 10^{13} \eta_{0.1}^{-0.38} M_4^{0.34} \text{ cm} \quad (5)$$

Strictly speaking, for (*inside-out*) outbursts starting in the inner disk regions the radius in Eq. (3) corresponds to the distance reached by the outside-propagating heating front. This distance can be shorter than the actual disk outer radius. In such case, the value given in Eq. (5) is only a lower limit for the disk radius. Note also that this assumes a non-irradiated disk. Taking into account irradiation of the outer regions of the disk by X-rays from the inner regions always moves the critical radius further out (Dubus et al. 1999). Alternatively, an irradiation-dominated disk reprocessing passively $\mathcal{C} \approx 0.1$ of the X-ray luminosity would still see its temperature fall below 8000 K (hydrogen ionization) only for radii greater than $2 \times 10^{13} \text{ cm}$, similar to the above estimate. So, again, Eq. (5) is only a lower limit on the disk radius.

From the Kepler’s law a is

$$a = 6.3 \times 10^{12} M_4^{1/3} P_d^{2/3} \text{ cm}, \quad (6)$$

¹¹ 373 days according to Kong (2011)

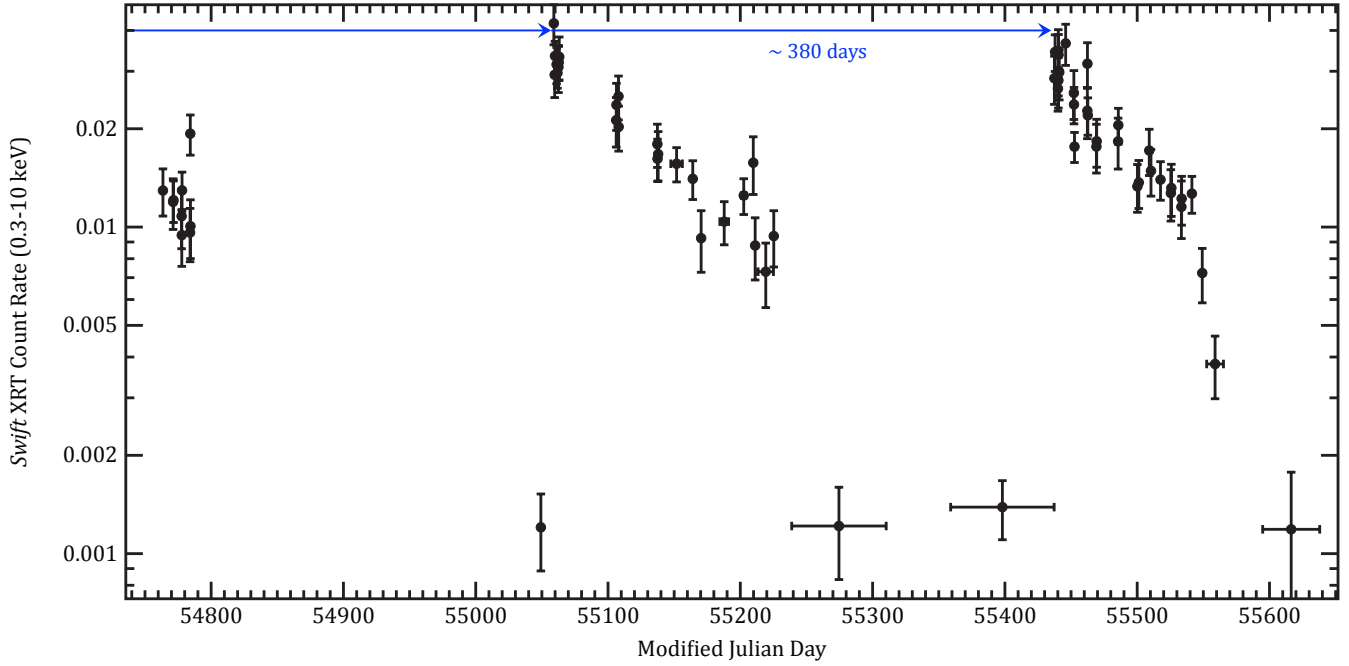


Figure 1. The 2008 - 2011 *Swift*-XRT Photon Counting grade 0-12 light-curve of HLX-1 in the 0.3-10 keV energy range.

with P_d being the orbital period (in days). Combining with Eq.(2), the mean density of the companion $\bar{\rho}$ can be written in terms of the orbital period only

$$\bar{\rho} \approx 0.057 P_d^{-2} \text{ g cm}^{-3}. \quad (7)$$

A disk size $R_D \gtrsim 5 \times 10^{13}$ cm implies an orbital period $\gtrsim 23$ days. The secondary star mean density for the hypothetical companion of HLX-1 gives $10^{-4} \text{ g cm}^{-3}$ suggesting a red giant or a massive supergiant. A priori, this is consistent with several possible evolutionary scenarios for HLX-1 (Farrell et al. 2010, but see Sect. 3).

2.2. Outburst properties

The presumed outburst of HLX-1 does not look like a “standard” full-blown outburst of a black-hole transient low-mass X-ray binary. In all such phenomena, after the outburst, the system declines (sometimes after one or two re-bounds) to a quiescent, very-low luminosity state. According to the DIM the (non-constant) accretion rate is then everywhere lower than the critical value given by Eq. (3) (in fact it is lower than the lower critical value \dot{M}_{crit}^-). Assuming that the disk terminates at the ISCO (Innermost Stable Circular Orbit) this implies a luminosity of $< 2 \times 10^{30} \text{ erg s}^{-1}$. Even allowing for inner disk evaporation one can only increase this luminosity by 4 or 5, say, orders of magnitude (Lasota et al. 1996; Menou et al. 2000; Dubus et al. 2001), still well below the observed $\sim 2.6 \times 10^{40} \text{ erg s}^{-1}$.

2.3. Irradiation dominated disk

The moderate amplitude of the outburst in HLX-1 suggests that only part of the disk is involved *i.e.* that the DIM heating and cooling fronts propagate only in a restricted domain of the disk. Cooling fronts can be stalled when X-ray irradiation from the inner regions of the disk

prevents cooling in the outer regions. If the disk irradiation is directly tied to the mass accretion rate onto the compact object this does not prevent the disk from emptying but the decay light curve falls down exponentially (King & Ritter 1998; Dubus et al. 2001). More complicated behavior can arise if X-ray irradiation is not directly tied to the inner mass accretion rate.

Here, irradiation by a hot supergiant star located just outside of the disk can have an impact on its stability, independently of the mass accretion rate. Such a possibility has been advocated by Revnivtsev et al. (2002) in the case of outbursts of the (presumably) super-Eddington source V4641 Sgr. Such irradiation would be constant in time (or at least accretion-independent) and its effects different from the accretion self-irradiation. Constant irradiation of an unstable disk typically leads to long term, low-amplitude modulation of the inner mass accretion rate. An example calculation is shown in Dubus (2005). The cooling front propagates inward down to the radius where constant irradiation keeps the disk hot. The region participating in the instability is limited with little of the disk mass accreted at each cycle.

Although determining the exact timescale and amplitude of the modulation requires numerical calculations, the typical outburst timescale will be linked to the viscous timescale of the minimum unstable radius (where the temperature must be $\approx 10^4$ K)

$$t_{\text{vis}} = \frac{R^2}{\nu} \approx 115 \alpha^{-1} T_4^{-1} R_{13}^{1/2} M_4^{1/2} \text{ years}, \quad (8)$$

T_4 is the disk temperature in units of 10^4 K and we have used the Shakura-Sunyaev prescription for the kinematic viscosity coefficient $\nu = \alpha c_s^2 / \Omega_k$. For comparison, the case shown in Dubus (2005) had a modulation period of about 0.5 years but had $R_{13} \approx 0.01$ and $M_4 \approx 0.001$. The model appears difficult to reconcile with the fast timescale of the variations in HLX-1. The disk must

be at least as large as required by Eq. (5) (actually larger by a factor 2 when including irradiation heating) in order to be unstable in the first place. In order to obtain small amplitude outbursts, the radius to which the cooling front propagates (Eq. 8) cannot be orders-of-magnitude lower than the outer disk radius. The modulation timescale will be too long for any reasonable set of parameters. We conclude that the variability in HLX-1 is unlikely to be related to the DIM in the sense that it is difficult to reconcile the timescales with a disk large enough that its temperature at the outer radius is below $\approx 10^4$ K. Therefore the accretion disk in HLX-1 is very likely to be hot and thermally stable.

2.4. Radiation-pressure dominated disk

We note that in considering the origin of HLX-1's variability one should take into account that it is a near-Eddington X-ray source. For $L/L_{\text{Edd}} \gtrsim 0.01$ the standard Shakura-Sunyaev disk is radiation-pressure dominated and opacities are due mainly to electron-scattering. Such a disk is thermally and viscously unstable and the resulting variability has been modeled producing FRED-like outbursts with amplitude factors $\lesssim 100$ (Taam & Lin 1984; Lasota & Pelat 1991; Szuszkiewicz & Miller 2001), thus interesting in the context of HLX-1. The unstable region is limited to the inner $\sim 100R_g$ from the black hole so it is generally short although Mayer & Pringle (2006) find a recurrence time of ≈ 250 years for the case of a $10^6 M_\odot$ black hole accreting at 10% of the Eddington rate. Contrary to the case of the dwarf-nova DIM, the physics of the radiation-pressure thermal instability is rather controversial (Hirose et al. 2009a,b). It remains to be seen whether the amplitude and recurrence time of the variability in HLX-1 can be reproduced by a radiation-pressure dominated disk around a $10^4 M_\odot$ black hole (Zheng et al. 2011; Ciesielski et al. 2010).

3. ORBITAL ORIGIN OF THE LONG-TERM VARIABILITY

We have shown above that the disk-instability origin of the observed long term variability is very unlikely. Here, prompted by the recurrent nature of the X-ray flux variations, we consider whether the variability could be orbital in origin.

3.1. Orbital modulation

Other ULX systems, such as X41.4+60 in M82 and NGC 5408 X-1 are variable on timescales of 62 and 115 days respectively (Kaaret et al. 2006; Strohmayer 2009). These variations have been interpreted as reflecting orbital modulations. As with those systems, the companion star of HLX-1 would have to be a massive supergiant star ($\bar{\rho} \approx 10^{-7} \text{g cm}^{-3}$) if the 380 day timescale is the orbital period. One mechanism that would cause the X-ray modulation is absorption and scattering by the companion's stellar wind. However, this explanation is unlikely for HLX-1 for three reasons. First, the X-ray flux is modulated only by a factor ~ 2 in the case of the aforementioned ULX sources compared to a factor 20 – 50 in HLX-1. Second, their light-curves are quasi-sinusoidal in contrast with the FRED-like shape of HLX-1. Finally, the observations of HLX-1 do not show a significant change in the X-ray absorption column density

at different luminosity levels (but this is challenging to constrain within the statistical quality of the X-ray data available).

Recently King (2011) proposed that ULXs in globular clusters could be Ultra Compact X-ray Binaries (UCXBs) in which a neutron star accretes, at slightly super-Eddington rates, matter lost by a Roche-lobe filling companion white dwarf. King (2011) suggested that a version of this model might apply to HLX-1 but left the 380-day variability unexplained. In such a scenario one could be tempted to identify this variability with the so-called super-orbital period observed e.g. in the UCXB 4U 1820-303, where a variability 170 days is observed in addition to the orbital period of ~ 11 minutes is observed (see Zdziarski et al. 2007b, and references therein). In this system the intrinsic luminosity varies by a factor of $\gtrsim 2$ only but larger amplitudes could be envisaged in the framework of a hierarchical triple system model (Zdziarski et al. 2007a). However, the hardness-intensity relation in 4U 1820-303 shows a pattern completely different from that observed in HLX-1. Of course, as mentioned by King (2011), if the H_α line is emitted by the accretion flow the UCXB model is ruled out. Clearly more observations in the optical domain are required to decide the viability of this (and other) models.

3.2. Modulated mass transfer from a donor in an eccentric orbit

A scenario in which the disk in an eccentric binary would exist semi-permanently (the viscous time of a standard accretion disk being long, see Eq. (8)) and outbursts would be triggered by increased mass-transfer rate during the passage of the companion appears to be the only serious possibility left. It would be, in a sense, the equivalent of the so-called mass-transfer instability model advocated previously for dwarf-nova stars (Bath & Pringle 1981). In the case of HLX-1 one has to show that such an binary system can be formed and survive long enough to be observed. Here, we present the outline of such a scenario, which we explore in more detail elsewhere (Alexander, Dubus & Lasota 2011). One uncertainty is how eccentric the orbit must be to allow fast enough accretion that can reflect the orbital modulation. The simple assumptions we make here are not expected to hold for very high eccentricity, but they can provide an upper limit on the probability of an eccentric binary donor in HLX-1.

3.2.1. The set-up

For the moment observations provide only very general constraints on possible evolutionary models of our hypothetical binary system. As an example we assume here that the $P_\star \approx 380$ d period observed in the X-ray light curve of HLX-1 reflects the orbital period of an evolved donor of mass M_\star and radius R_\star , in an eccentric orbit around an IMBH of $M_\bullet \sim \mathcal{O}(10^4 M_\odot)$. To feed the accretion (quasi)-periodically, the orbit must graze the tidal disruption radius $r_t \simeq R_\star (M_\bullet/M_\star)^{1/3}$ at periape, $r_p = a_\star(1 - e_\star)$, where a_\star is the orbital semi-major axis (sma), and e_\star the eccentricity. Therefore one obtains

$$a_\star \simeq 22.1 \text{ AU} \left(\frac{P_\star}{380 \text{ d}} \right)^{2/3} \left(\frac{M_\bullet}{M_\odot} \right)^{1/3}, \quad (9)$$

(22.1 AU = 7×10^{14} cm). The extremely high mass-loss requirement of $\mathcal{O}(10^{-4} M_\odot \text{yr}^{-1})$ strongly suggests an AGB donor (initial mass range of $\sim 0.5 M_\odot$ to $10 M_\odot$; Habing & Olofsson 2003), which can reach $\sim 10^{-5} - 10^{-4} M_\odot \text{yr}^{-1}$ mass-loss rate even without “tidal induce-ment” (Bowen & Willson 1991). We will adopt here as a fiducial AGB progenitor a $M_\star = 4 M_\odot$ star with a main-sequence (MS) radius of $2.3 R_\odot$ and therefore a MS lifetime of $t_\star \simeq 200$ Myr, which expands to $R_\star \sim 100 R_\odot$ in the AGB phase. The eccentricity required to graze the tidal radius is then

$$1 - e_t = r_t / a_\star \simeq 0.3 \left(\frac{R_\star}{100 R_\odot} \right) \left(\frac{M_\star}{4 M_\odot} \right)^{-1/3} \left(\frac{P_\star}{380 \text{ day}} \right)^{-2/3} \quad (10)$$

While still on the MS, the donor orbit is stable to both tidal and gravitational wave decays, since $r_p \sim 75 r_t \sim 10^5 r_g$. However, once it reaches the AGB phase, it will be quickly destroyed within $10^4 - 10^5$ yr, due to a combination of the high mass loss rate and the tidally driven orbital decay.

The scenario proposed here is different from the one suggested by Hopman et al. (2004) to explain the non-periodic ULX in the young cluster MGG-11 in M82. There, it was assumed that the progenitor was tidally captured while still on the MS, and that the orbit decayed and circularized by the tidal interaction before the star reached the AGB, resulting in a relatively steady mass transfer rate on a very short-period circular orbit evolving through emission of gravitational radiation.

3.2.2. Evolution and survival

Run-away stellar mergers in the dense collapsed cores of young clusters are widely considered to be a natural pathway to the formation of an IMBH (Ebisuzaki et al. 2001; Portegies Zwart & McMillan 2002; Gürkan et al. 2004; Freitag et al. 2006b,a). The scenario considered here is based on the simulations by Gürkan et al. (2004, hereafter GFR04)¹². They find that for a wide range of initial parameters, a dense cluster with a broad Initial Mass Function (IMF) will undergo mass segregation and core collapse after a time $t_{CC} \sim 0.1 t_{r,1/2}(0)$, where $t_{r,1/2}(0)$ is the initial 2-body relaxation at the half-mass radius of the cluster. When the core-collapse time is shorter than the minimal MS lifetime for massive stars

$$t_{CC} < \min t_\star \sim 3 - 4 \text{ Myr}, \quad (11)$$

the massive stars that segregate in the dense collapsed core can undergo run-away mergers on a timescale shorter than the stellar evolutionary timescale. If the merged “super-star” can cool fast enough and avoid rapid mass loss, it may collapse to form an IMBH.

Guided by the GFR04 simulations, in what follows we will assume that this process forms an IMBH with a mass ratio $M_\bullet / M_c = 0.002$, where M_c is the total initial mass

¹² A scenario in which a nucleated dwarf galaxy is undergoing a period of accretion due to a recent passage through the host galaxy is often mentioned in the context of HLX-1. Although the presence of IMBH in nuclei of dwarf galaxies has still to be demonstrated (see e.g. Reines et al. 2011) we think we are justified in considering this possibility just as a slightly different realization of the scenario we are studying.

of the cluster. As reference we will use Model 2 of GFR04 in which a Salpeter IMF extending from $0.2 - 120 M_\odot$ is assumed (mean mass $\langle M_\star \rangle = 0.7 M_\odot$, $\max M_\star / \langle M_\star \rangle = 174$). The model assumes a Plummer distribution with a length-scale $R_c = (2^{2/3} - 1)^{1/2} r_{1/2} \simeq 0.766 r_{1/2}$, where $r_{1/2}(0)$ is the initial half mass radius. The core-collapse time is:

$$t_{CC} \approx 4.7 \frac{N_6}{\log 10^4 N_6} \frac{1}{\sqrt{\rho_9}} \text{ Myr} \quad (12)$$

where $\rho_0 = (10^9 M_\odot \text{pc}^{-3}) \rho_9$ is the initial central density and $N_c = 10^6 N_6$ is the stellar number. The condition $t_{CC} < 3$ Myr then translates to $\rho_0 \gtrsim 10^9 M_\odot \text{pc}^{-3}$ (for $M_c = 5 \times 10^6 M_\odot$, $N_c = 7.25 \times 10^6$, $R_c = 0.11$ pc). Although young clusters and super star clusters with relaxation times well below 30 Myr are observed (Figer et al. 2002; Ho & Filippenko 1996) it is less clear whether such extreme central densities are realized in nature. A lower IMBH mass will ease this problem since according to Eq. (12), $\rho_0 \sim M_\bullet^2$.

In such dense systems mass segregation proceeds very rapidly and accelerates the evolution toward core collapse. Following the results of GFR04 (their Fig. 5) we take for the stars closest to the newly formed IMBH $\langle M_\star \rangle_h = 4 M_\odot$, with a corresponding radius $\langle R_\star \rangle_h = 2.34 R_\odot$, as the mean stellar mass and radius within the IMBH radius of influence, $r_h = GM_\bullet / \sigma_c^2$, where σ_c^2 is the typical 1D velocity dispersion of the host cluster ($\sigma_c^2(0) = GM_c / 6 R_c \simeq 185 \text{ km s}^{-1}$ for the Plummer model here). It is noteworthy that mass segregation initially concentrates intermediate mass AGB progenitors near the IMBH.

Following the collapse the dynamical response of the cluster by mass segregation and expansion leads to the formation of a relaxed stellar cusp inside r_h , with $n_H(r) \propto r^{-\alpha_H}$ ($\alpha_H = 7/4 - 5/2$) for the massive stars, and $n_L(r) \propto r^{-3/2}$ for the low-mass stars (Bahcall & Wolf 1977; Alexander & Hopman 2009; Keshet et al. 2009; Preto & Amaro-Seoane 2010). The cusp extends inward down to the collision radius, $r_{in} = \max(r_t, r_{\text{coll}}) = r_{\text{coll}} \sim (M_\bullet / M_\star) R_\star$, at which 2-body relaxation ceases to be effective because velocities are so high that only physical collisions can substantially change the stellar orbits (Frank & Rees 1976). For a standard MS mass-radius relation this gives

$$r_{\text{coll}} \sim 48.7 (M_\bullet / 10^4 M_\odot) (M_\star / M_\odot)^{-0.43} \text{ AU}, \quad (13)$$

so that for the cusp to extend down to $a_\star \simeq 22$ AU the stars must be more massive than $\sim 3.7 M_\odot$. One notices that this lower limit coincides with the mass range predicted by pre-IMBH mass segregation, while being low enough to include AGB progenitors.

Equilibrium is established when the flux of gravitational binding energy that is released when stars are destroyed by the IMBH equals the flux carried by the expanded cluster core (Heggie et al. 2007). Assuming a Plummer initial distribution one obtains the mass of the cusp M_h as (e.g. Baumgardt et al. 2004)

$$M_h \simeq [648 / (3 - \alpha_H)] (M_\bullet / M_c)^2 M_\bullet. \quad (14)$$

In contrast to the radius of influence of a supermassive black hole (SMBH) in an approximately isothermal

galactic nucleus, that of an IMBH contains only a very small number of stars, $N_h = M_h / \langle M_\star \rangle_h \sim \mathcal{O}(10)$.

Equations (12) and (14), together with the system parameters M_\bullet , M_\bullet/M_c , α_H , $\langle M_\star \rangle$ and $(\langle M_\star \rangle_h, \langle R_\star \rangle_h)$ fully describe the IMBH cusp structure and properties in this simplified model, and allow calculating the mean number of stars on orbits with $a \leq a_\star$ and $e \geq e_\star$, $\langle N_{a,e} \rangle = N_h [(5/4)a_\star/r_h]^{3-\alpha_H} (1 - e_\star^2)$, where an isotropic cusp is assumed. The Poisson probability for having at least one star on a donor orbit is then $P_1 = 1 - \exp[-\langle N_{a,e} \rangle]$.

The cusp mass and its stellar density rise with the IMBH mass (Eq. 14). As a consequence, P_1 increases with M_\bullet , but with it also the rate of destructive stellar collisions, and the drain rate (star-star scatterings into the IMBH, Alexander & Livio 2004). Over the relevant range of IMBH masses, P_1 rises from $\lesssim 10^{-3}$ to $\gtrsim 0.1$. The IMBH mass that maximizes P_1 subject to both the collisional and drain constraints lies in the range of $\text{few} \times 10^3 M_\odot$, with $\text{max } P_1 \sim \text{few} \times 0.01$.

The observed residual UV fluxes from HLX-1, after subtracting a disk model and correcting for extinction ($E_{B-V} = 0.042$), are $4.8 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ ($L_{\text{NUV}} = 5.2 \times 10^{39} \text{ erg s}^{-1}$ for isotropic emission at $D = 95 \text{ Mpc}$) in the NUV ($2147 \text{ \AA} - 3467 \text{ \AA}$), and $4.7 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ ($L_{\text{FUV}} = 5.1 \times 10^{39} \text{ erg s}^{-1}$) in the FUV ($1233 \text{ \AA} - 1821 \text{ \AA}$) (based on a preliminary analysis of HST data, Farrell et al., in preparation). These place constraints on the properties of the hypothesized birth cluster of the IMBH.

Stellar population synthesis models together with model atmospheres allow to predict the UV flux as function of the IMF, metallicity and age of the system. Generally, the older the cluster, the less UV it emits. An older cluster directly implies a lower mass AGB progenitor, that can spend longer on the MS. Preliminary modeling, both assuming black body spectra, and using detailed stellar atmosphere models (the STARS code, Sternberg 1998) indicates that a minimal cluster age of $\sim (0.3 - 0.6) \text{ Gyr}$ is required for the cluster's UV luminosity to fall below the residuals (Assuming a cluster mass of $5 \times 10^6 M_\odot$ and solar metallicity). This corresponds to an AGB progenitor of $\sim (2.7 - 3.5) M_\odot$. Such longer-lived progenitors are more susceptible to collisional destruction and scattering into the IMBH, but are still probable at the $P_1 \sim \text{few} \times 0.01$ level. The constraints on the AGB progenitor mass could be relaxed somewhat by assuming a higher value of M_\bullet/M_c , and possibly by assuming a different metallicity. This requires a more systematic study.

After mass transfer starts in the AGB phase, 2-body perturbations from other stars can be neglected, since the relaxation time at r_h is $t_h \sim \text{few} \times 10^6 \text{ yr}$, and the timescale to significantly affect the orbital eccentricity, $(1 - e_\star^2)t_h$, is longer than the $\sim 10^4 \text{ yr}$ maximal lifetime of the donor, for all relevant values of the eccentricity.

Thus, while an IMBH with $M_\star \sim 10^4 M_\odot$ is not excluded in the context of the eccentric donor scenario, observations and theoretical considerations favor a somewhat less massive IMBH with $M_\bullet \sim \text{few} \times 10^3 M_\odot$, still consistent with the constraints derived from the observed accretion emission (see Sec. 1).

To summarize, we used a simplified model, based on results from N -body simulations of runaway merger for-

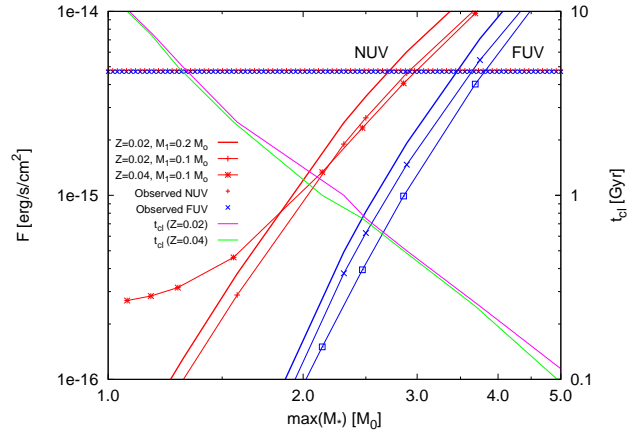


Figure 2. A comparison of the observed de-reddened limits of the residual UV fluxes (after subtraction of a disk model) to stellar population synthesis model predictions for different metallicities (Z) and low mass cutoffs (M_1) and assuming a $5 \times 10^6 M_\odot$ cluster, as function of the maximal progenitor mass (the turn-off mass), which sets the age of the cluster (also shown) and hence its minimal UV luminosity.

mation of a seed IMBH, to predict the stellar distribution around a newly formed IMBH. We estimated the probability of finding an AGB progenitor on an orbit that could explain the long period variability of HLX-1 in terms of mass transfer from an eccentric evolved donor. We find that between 1/100 to 1/10 of IMBHs with $M_\bullet \lesssim 10^4 M_\odot$ could have a $\text{few} \times 1 M_\odot$ MS star evolve to an AGB while avoiding collisional destruction or being scattered into the IMBH by 2-body encounters. An important caveat is that the validity of the model and our conclusions are limited by the neglect of the longer-term evolution of the cusp and host cluster, and in particular by the neglect of the effects of 2-body relaxation and fast resonant relaxation (Rauch & Tremaine 1996; Hopman & Alexander 2006) on the distribution of the stars around the IMBH.

The low probabilities are fully consistent with the apparent uniqueness of HLX-1. Theoretically we can only make statements about the conditional probability since we do not know the space density IMBH clusters but observationally, despite large-scale searches (in Chandra data by Liu (2011) and in XMM data by Walton et al. (2010)), there have not been any other HLX-1 like objects found. Most probably HLX-1 is alone in the local Universe.

3.2.3. Variability timescales

In our scenario involving a $1 - e = 0.3$ binary in which a star circles a $\sim 10^4 M_\odot$ black hole on an 380 day orbit, the periape will be at $\sim 10^{14} \text{ cm}$. The mass loss and disk formation processes is usually described by the star filling an “instantaneous” Roche lobe at periape (see e.g. Sepinsky et al. 2007; Lajoie & Sills 2011, in the context of high mass X-ray binaries). This description is increasingly inaccurate as the eccentricity grows but matter lost during the periape passage is expected to circularize at about this distance. The transferred material will have to diffuse inwards, on a viscous timescale. From the discussion in Sec.2, the disk is most likely hot with a temperature $\geq 10,000 \text{ K}$ at the outer edge. The diffusion timescale for the transferred material would be hundreds

of years rather than days according to Eq. 8. As a result, the accretion timescale will smooth out the bursts in mass transfer.

One way out of this difficulty is to increase the disk temperature. Irradiation is unlikely to increase the disk temperature much: the irradiation temperature $T_{\text{irr}} = (\mathcal{C}L_X/4\pi\sigma_{\text{SB}}R^2)^{1/4}$ is ≈ 3500 K at 10^{14} cm (where $\mathcal{C} \approx 10^{-3}$ parametrizes our ignorance of the irradiation geometry and albedo, Dubus et al. 1999). Incoming material may shock heat the outer disk to high temperatures, especially in the case of a tidal disruption on a parabolic orbit when the material ejected from the star has a large range of velocities relative to the Keplerian disk velocity, up to the escape speed of the star (see e.g. Rees 1988). The response of the disk to a burst of mass transfer in this situation has not been modeled. Note, however, that in close low-mass binary systems the “hot spot” resulting from the mass-transfer stream impact significantly heats the outer disk without drastically affecting the dynamical properties of the disk because the thermal timescale on which the extra heating is radiated away in a thin disk is much shorter than the viscous timescale (Buat-Ménard et al. 2001; Smak 2002).

Another way to reduce the diffusion timescale is to reduce the periaapse distance. The viscous timescale is already down to 3 years if periaapse is at $r_t \sim 10^{12}$ cm (assuming the temperature varies as $T \sim R^{-1/2}$, in Eq. 8). In such a model the disk does not disappear completely in between mass transfer episodes (in accord with the non-zero minimum flux) and the impulsive increase in mass transfer leads to increase in lightcurve on timescales more like a fraction of t_{vis} ($\lesssim 0.1$) and then decays on t_{vis} or so. The passage of the star at periaapse may also lead to the excitation of waves in the disk that will enhance angular momentum transport (Spruit 1987). Tidal waves may provide an additional source of heating in the disk. The price to pay is that such a binary has a much lower probability because (1) the orbit must be nearly parabolic, $e \rightarrow 1$, (2) the depletion of the phase space density of orbits near the loss cone, which was not taken into account in our simple estimate (sec. 3.2.2), and (3) the unstable nature of such an orbit. In fact, this instability could lead to an observed complete disruption within a few orbits (few years).

4. DISCUSSION AND CONCLUSIONS

The extremely high luminosity, light curve shape and X-ray spectrum evolution of HLX-1 point toward disk accretion around a $10^4 M_\odot$ black hole fueled by a Roche-lobe filling star. We have examined the conditions under which the X-ray variability might be explained by the disk instability model. We find this requires an accretion disk much too large for corresponding timescales to be compatible with the observed X-ray variability. Any accretion disk around HLX-1 is most likely small enough to be hot and stable against the DIM. One cannot exclude that the variability is due to the instability that can arise in radiation-pressure dominated disks. However, the physics behind this instability is not well known and it is not clear whether this will lead to the correct outburst amplitude and timescales.

The variability would be much easier to explain with a stellar-mass black hole but the luminosity would obviously be problematic. Conversely, the luminosity is

no issue for a supermassive black hole but the amplitude and timescales would be an insurmountable problem (Hameury et al. 2009).

We have shown, however, that a viable description of the HLX-1 variability can be provided by a model in which enhanced mass transfer into a quasi-permanent accretion disk is triggered by the passage at periaapse of an evolved (AGB) star circling the IMBH on an eccentric orbit. Using a simplified model based on the results of N-body simulations we concluded that such systems, although not common, are realistically observable. However, the actual response of a standard accretion disk to bursts of mass transfer may be too slow to explain the observations unless the orbit is close to parabolic and/or additional heating, presumably linked to the highly time-dependent gravitational potential, is invoked.

The validity of our conclusions is limited by the neglect of the longer-term evolution of the cusp and host cluster, in particular by neglecting the effects of 2-body relaxation and fast resonant relaxation on the distribution of the stars around the IMBH. In general, the very small number of stars in the IMBH cusp casts doubts on the applicability of the statistical approaches commonly used to analyze dynamics around SMBHs. In addition, the comparatively high density of unbound (cluster) stars in the cusp complicates the analogy with known results from SMBH cusp dynamics. Progress in the analysis of the post-formation evolution of IMBHs will require time-dependent modeling and N-body simulations.

The further evolution of the intriguing variability pattern of HLX-1 (periodicity, amplitude) as well as observations of its optical counterpart should shed light on the origin and nature of this extraordinary system.

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